



Influence of Different Nutrient Management Strategies on Growth, Yield and Greenhouse Gas Emissions of Irrigated Rice



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Article History:

Received: 19th Jun., 2025

Accepted: 16th Nov., 2025

Published: 30th Dec., 2025

Keywords:

Greenhouse gas emission,
Leaf colour chart, Nano urea,
Decision support tools,
Sufficiency index

How to cite this Article:

Lalichetti Sagar, Sagar Maitra, Sairam Masina and Sumit Ray (2025). Influence of Different Nutrient Management Strategies on Growth, Yield and Greenhouse Gas emissions of Irrigated Rice. *International Journal of Experimental Research and Review*, 49, 01-09.

DOI:

<https://doi.org/10.52756/ijerr.2025.v49.001>

Abstract: In the era of climate change, it is not ideal to rely on nutrient management strategies that were solely designed to enhance the grain yield of rice because their adoption often increases greenhouse gas emissions, posing a serious threat to the environment. In this backdrop, the present research was conducted to identify the most effective approach that can balance high crop productivity with a limited carbon footprint. The field experiment was carried out during the *rabi* season of 2022-23 in randomized block design with eleven nutrient management treatments and three replications. The results revealed that SI₉₀ reported significantly higher plant height, tiller density, leaf area index and dry matter accumulation. Similarly, apart from 1000 grain weight, significantly higher numbers of panicles and number of filled grains per panicle were recorded by SI₉₀. Further, both growth and yield parameters reported a strong positive correlation with the grain yield of rice attributing significantly higher grain yield which was on par with CN₁₂₅, LCC₄ and NU₁₀₀. However, from the PCA analysis it was evident that unlike other treatments the SI₉₀ achieved significantly higher grain yield with a moderate level of GHG emission. Therefore, it could be the most effective approach and future research on nutrient management should be focused on need-based nutrient application accompanied by crop intensification to provide adequate food to the growing population with a limited carbon footprint.

Introduction

In the present era of climate change, establishing an ideal balance between global food security and environmental sustainability has become a major challenge (Ray et al., 2024; Paul et al., 2024; Das et al., 2024; Santosh et al., 2024). The increased use of synthetic inputs, particularly chemical fertilizers, has significantly contributed to the rise in greenhouse gas emissions from agriculture (Maitra et al., 2025; Ray et al., 2025). Rice cultivation receives considerable attention in this scenario because it consumes a substantial portion of fertilizers used in the country and is often cultivated under waterlogged soils, resulting in greater methane gas emissions (Hossain et al., 2021). As a consequence, rice ecosystems were identified as a prime source of greenhouse gas emissions from

agriculture, which were further aggravated by unprecedented nutrient management.

To address this situation effectively, adopting well-defined nutrient management that appropriately synchronizes crop demand with nutrient supply could be an effective approach. Among the different nutrient management strategies, site-specific nutrient management is gaining traction due to the availability of diagnostic and optical sensors and ICT-based decision support tools (Sagar et al., 2024). These tools can assist farmers in assessing the critical period for nutrient application and help them in taking appropriate decisions on nutrient management, aimed at enhancing nutrient use efficiency (Qian et al., 2023).

Moreover, the recent introduction of IFFCO nano urea has opened new avenues for nutrient management (Samanta et al., 2022; Sumui et al., 2022). In comparison



with conventional urea, the nano urea reported higher efficiency in rice cultivation due to greater surface area and nano particle size (Sagar et al., 2022; Das et al., 2025). Therefore, judicious supplementation of nano urea with the recommended dose of fertilizers ought to enhance the nutrient use efficiency by reducing nutrient losses to the environment.

Both site-specific nutrient management and nanotechnology can improve nutrient-use efficiency and mitigate greenhouse gas emissions from rice cultivation. However, the comparative assessment of conventional fertilizer practices, nano-nitrogen integration, diagnostic and sensor-based nitrogen management, and ICT-based nutrient recommendations in terms of their relative effectiveness was meager. Therefore, the present study was conducted.

Materials and Methods

Table 1. Description of nutrient management treatments.

Treatment code	Description
NM ₀	Nutrient omission control
CN ₇₅	Reduced conventional fertilization (75% RDF)
CN ₁₀₀	Standard conventional fertilization (100% RDF)
CN ₁₂₅	High conventional fertilization (125% RDF)
NU ₇₅	CN ₇₅ + nano urea*
NU ₁₀₀	CN ₁₀₀ + nano urea*
LCC ₃	Leaf colour chart (LCC)-guided N Management (Threshold 3)
LCC ₄	LCC-guided N Management (Threshold 4)
SI ₉₀	Sufficiency Index (SI)-based N management (SI < 90%)
NE-R	Nutrient Expert (NE)-guided nutrient recommendation
RCM-R	Rice Crop Manager (RCM)-guided nutrient recommendation
*Foliar spray of nano urea @ 2 ml L ⁻¹ at panicle initiation	

The field experiment was carried out during the *rabi* season of 2022-23 at the Post Graduate Research Farm of M.S. Swaminathan School of Agriculture, Centurion University of Technology and Management, Odisha, India (18°48'18"N and 84°10'45"E, with an elevation of 88 meters above sea level). During the crop growing period, the maximum temperature ranged between 28.4°C

and 39.1°C, while the minimum temperature ranged between 13.1°C and 23.7°C. The relative humidity during the morning ranged from 80.6% to 90.7%, which was higher than during the afternoon, which ranged between 37.4% and 69.6%.

Table 2. Fertilizer application schedule during the crop growing period.

Treatments	N Application Schedule (kg ha ⁻¹)	P ₂ O ₅ (kg ha ⁻¹)	K ₂ O (kg ha ⁻¹)	Nano urea (ml L ⁻¹)
NM ₀	NIL	0	0	-
CN ₇₅	Basal (45), AT (22.5), PI (22.5)	45	45	-
CN ₁₀₀	Basal (60), AT (30), PI (30)	60	60	-
CN ₁₂₅	Basal (75), AT (37.5), PI (37.5)	75	75	-
NU ₇₅	Basal (45), AT (22.5), PI (22.5)	45	45	2
NU ₁₀₀	Basal (60), AT (30), PI (30)	60	60	2
LCC ₃	Basal (33), 35 DAT (33), 56 DAT (33)	60	60	-
LCC ₄	Basal (33), 35 DAT (33), 42 DAT (33), 56 DAT (33)	60	60	-
SI ₉₀	Basal (60), 21 DAT (30), 35 DAT (30), 56 DAT (30)	60	60	-
NE-R	Basal(35) , 15 DAT (33), 30 DAT (33)	35	58	-
RCM-R	Basal (35), 23 DAT (41), 41 DAT (42)	33	27	-
*AT=active tillering; PI=panicle initiation; DAT=days after transplanting				

The crop was raised under irrigated conditions as the total rainfall received during the study period was only 110 mm. The experiment was laid out in a randomized block design with eleven treatments (Table 1) and three replications under sandy loam textured soil, which was slightly acidic, low in organic carbon, low in available nitrogen, medium in available phosphorus, and medium in available potassium. The variety used in this experiment was Naveen (IET 14461, CR 749-20-2), which was sown on 1st December, 2022, in the nursery and the seedlings were transplanted to the main field on 2nd January, 2023. The fertilizers were applied as per the

fertilizer application schedule mentioned in Table 2. The weeds in the experimental site were managed effectively by using pretilachlor 50% EC at 2.5 ml L⁻¹ as pre-emergence herbicide. Moreover, during the critical period of crop weed competition (20 and 40 DAT) of rice, the weeds were managed by hand weeding. The crop was harvested on 11th April, 2023, when 80 per cent of the grains were ripened and turned yellow. During the investigation, observations on growth, yield attributes and yield were recorded following standard agronomic procedures which were subjected to statistical analysis using analysis of variance (Panse and Sukhatme, 1984). The “agricolae” package in R was used to perform the least significant difference (LSD) test at 5% level of significance. The correlation analysis was performed to identify the relative contribution of different growth and yield parameters to grain yield. The treatments that varied significantly were presented with different superscripted letters, while the treatments that were at par were superscripted with the same letters. The relative potential of the treatments in GHG mitigation was estimated using CCAFS-MOT

(<https://ccafs.cgiar.org/research/projects/mitigation-options-tool-agriculture-ccafs-mot>). Further, principal component analysis was performed to identify the most effective nutrient management strategy that could establish a trade-off between yield and greenhouse gas emissions.

Results and discussion

Growth parameters

Table 3. Influence of different nutrient management strategies on growth parameters of rice.

Treatments	Plant height at harvest (cm)	Tiller density at harvest	Leaf area index at 60 DAT	Dry matter accumulation at harvest (g m ⁻²)
NM ₀	89±5.05 ^c	186±10.15 ^c	2.61±0.32 ^f	676±29.01 ^f
CN ₇₅	104±2.48 ^d	223±6.32 ^d	3.43±0.04 ^e	898±55.88 ^e
CN ₁₀₀	117±2.52 ^{abcd}	249±7.94 ^{ab}	4.38±0.05 ^{cd}	1083±44.02 ^{bcd}
CN ₁₂₅	121±4.52 ^{ab}	265±3.42 ^a	5.16±0.06 ^{ab}	1235±28.66 ^a
NU ₇₅	105±8.97 ^{cd}	226±2.85 ^b	3.64±0.08 ^e	978±84.07 ^{de}
NU ₁₀₀	119±2.83 ^{abcd}	252±13.23 ^{ab}	4.62±0.14 ^{bc}	1152±10.97 ^{abc}

LCC ₃	106±4.38 ^{bcd}	229±4.26 ^b	3.87±0.25 ^{de}	1005±18.92 ^{de}
LCC ₄	120±6.68 ^{abc}	256±6.54 ^{ab}	4.78±0.30 ^{bc}	1178±75.62 ^{ab}
SI ₉₀	124±6.67 ^a	267±11.31 ^a	5.36±0.05 ^a	1242±94.17 ^a
NE-R	109±0.99 ^{bcd}	230±29.84 ^b	3.91±0.31 ^{de}	1028±41.98 ^{cde}
RCM-R	115±2.48 ^{abcd}	243±9.85 ^{ab}	4.23±0.24 ^{cd}	1081±51.10 ^{bcd}
S.Em. (±)	5	12	0.19	53
CD (5%)	15	35	0.58	158

In the present study, the rice growth was expressed in terms of plant height, tiller density, dry matter accumulation recorded at harvest and leaf area index recorded at 60 DAS (Table 3). The perusal of data revealed that the highest plant height was noted by SI₉₀, which was at par with CN₁₂₅, LCC₄, NU₁₀₀, CN₁₀₀ and RCM-R. The statistical similarity between SI₉₀ and CN₁₀₀ revealed that applying 25 per cent more nitrogen, as guided by the sufficiency index at a threshold of 90, along with the recommended levels of phosphorus, did not significantly affect rice plant height. Moreover, NE-R, LCC₃, NU₇₅, CN₇₅ and NM₀ observed significantly lower plant height than SI₉₀. This might be mainly attributed to the application of nitrogen below the adequate levels at non-critical stages of crop growth. This discussion is consistent with Mohanta et al. (2021) and Sairam et al. (2023). The significantly lowest plant height was recorded by NM₀ treatment. Moreover, from the present study, it could be inferred that rice plant height was not influenced by nano urea supplementation, either at 75% RDF or 100% RDF. Similarly, the highest tiller density was recorded by SI₉₀ which was at par with CN₁₂₅, LCC₄, NU₁₀₀, CN₁₀₀ and RCM-R. This might be attributed to enhanced stimulation of cytokinin synthesis within the tiller nodes due to application of adequate nutrient doses and timely scheduling of split nitrogen application according to the crop demand. The attenuation of nitrogen, phosphorus and potassium concentrations to 75% RDF significantly decreased the tiller density. This discussion is in agreement with the findings of Attri et al. (2022) and Sagar et al. (2023a). An interesting finding from the present study was that CN₇₅ and CN₁₀₀ were at par with NU₇₅ and NU₁₀₀, respectively. In rice, crop ground coverage is ascribed to tiller density and hence plays a key role in determining the leaf area index. In the present study, SI₉₀ noted the highest leaf area index at 60 DAT, owing to adequate and demand-based nitrogen supply at recommended levels of

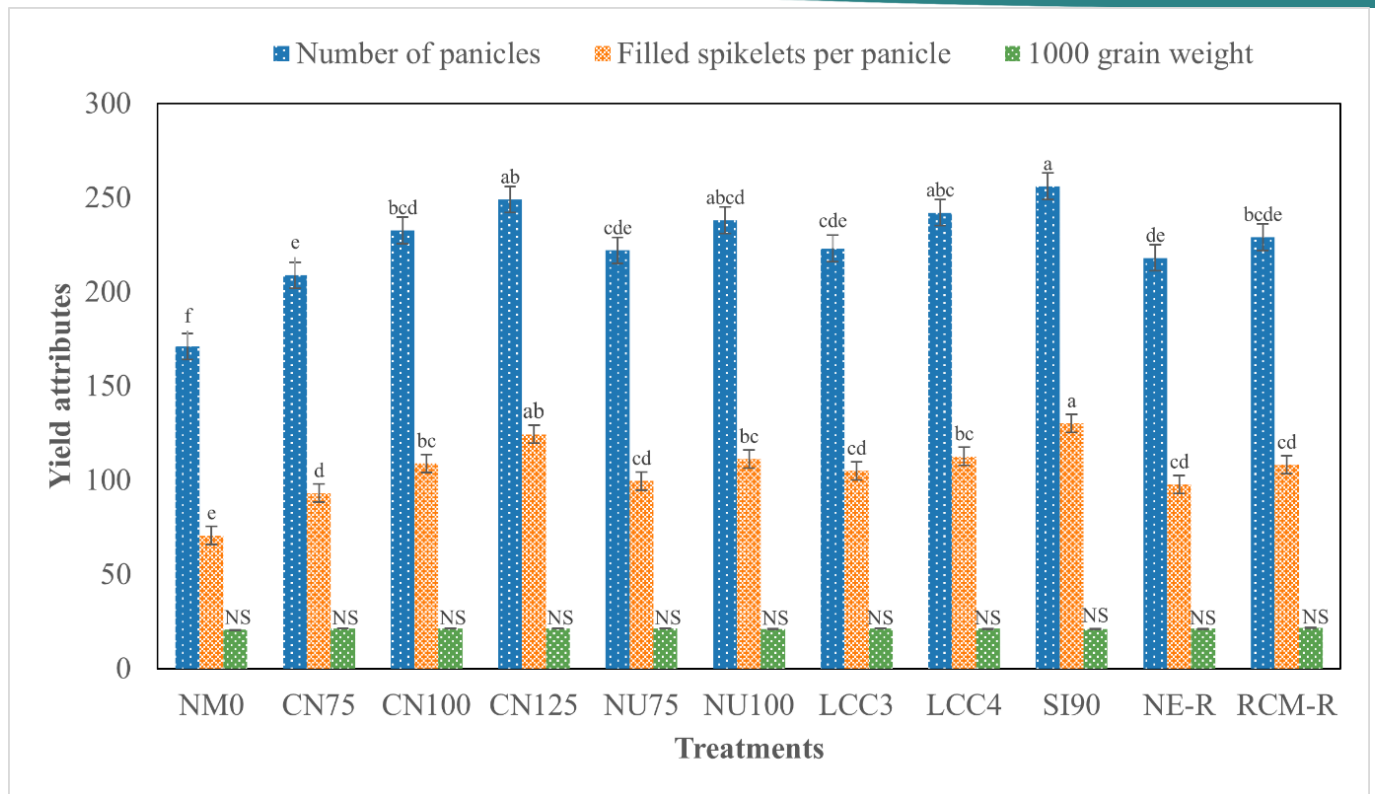


Figure 1. Influence of different nutrient management strategies on yield attributes of rice.

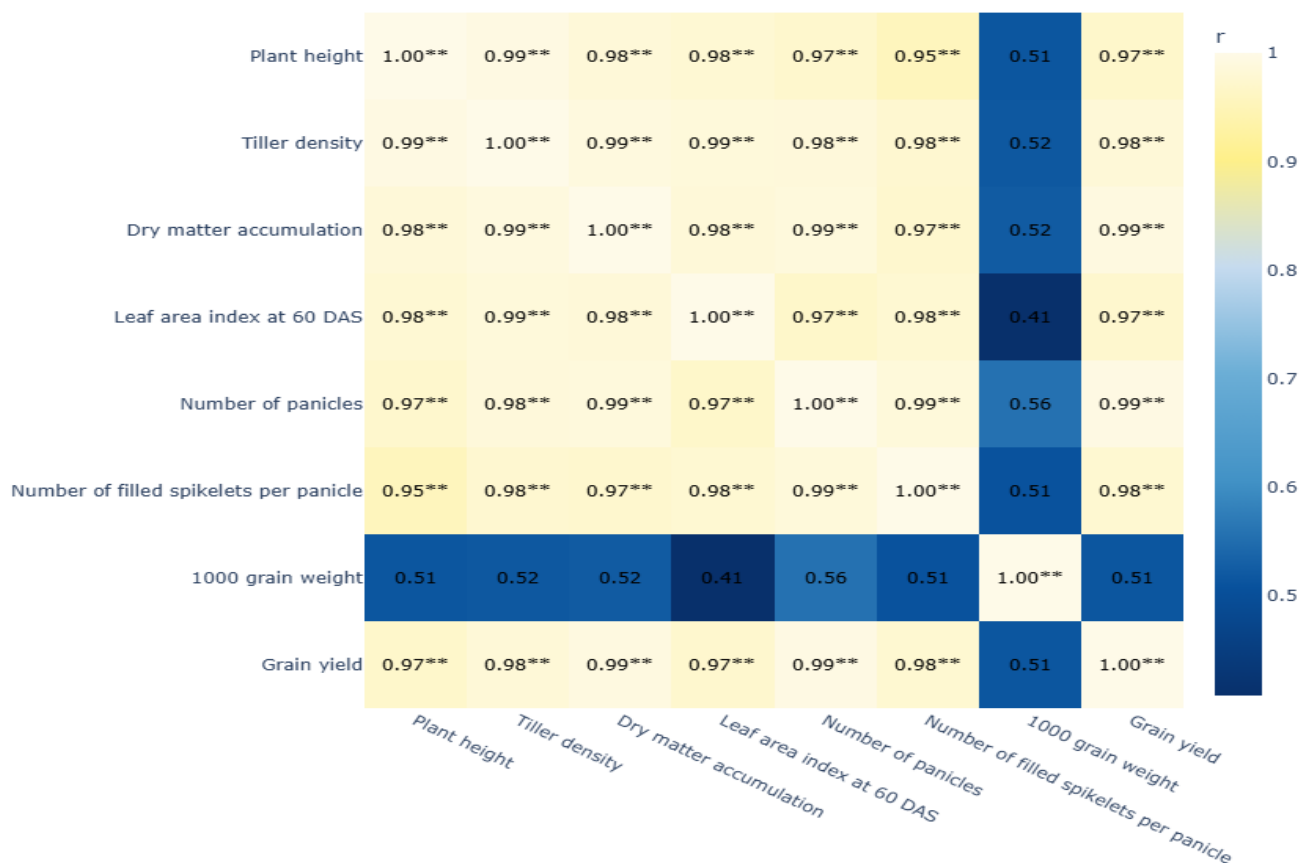


Figure 2. Correlation between growth and yield parameters on grain yield of rice.

** Significant at 1% level of significance

NS Non-significant

phosphorus and potassium. The former treatment was on par with CN₁₂₅. Similar findings were observed by Samanta et al. (2022) and Bhattarai et al. (2024). The highest dry matter accumulation of rice was recorded by SI₉₀, which was statistically indistinguishable from CN₁₂₅, LCC₄ and NU₁₀₀. The numerical superiority of SI₉₀ might be owed to the highest values recorded for plant height, tiller density, and leaf area index. Moreover, with the effective synchronization of nitrogen with the crop demand at recommended levels of phosphorus and potassium using the aforementioned index, it could even offset the advantage of increased N, P, and K levels applied at the recommended phase of crop growth. The former treatment was significantly superior to CN₁₀₀. Further, the latter treatment was on par with RCM-R, NE-R, LCC₃, and NU₇₅, while exhibiting significant superiority over CN₇₅ and NM₀, respectively. A similar discussion highlighting the advantages of real-time nitrogen management in rice at recommended phosphorus and potassium levels was reported by Sagar et al. (2023b) and Sairam et al. (2025).

Yield attributes

In the present investigation, the yield attributes of rice were represented by the number of panicles per square metre, the number of filled spikelets per panicle, and 1000-grain weight (Figure 1). The number of panicles per square metre and the number of filled spikelets per panicle of rice were significantly influenced by nutrient management, and SI₉₀ noted the highest values. The greater sink size by SI₉₀ might be due to adequate nitrogen availability during critical stages of nitrogen demand, which likely facilitated efficient assimilate translocation from source to sink. This discussion was supported by the earlier findings of Moharana et al. (2017) and Padhan et al. (2021). In terms of the number of panicles per square metre, the former treatment was on par with CN₁₂₅, LCC₄, and NU₁₀₀, while in terms of the number of filled spikelets per panicle, it was at par with CN₁₂₅. However, the 1000-grain weight of rice, being the most stable varietal trait, was not influenced by nutrient management treatments. Similar findings were observed by Kharlukhi et al. (2024) and Paul et al. (2025).

Correlation analysis

A correlation matrix is shown in Figure 2 to illustrate the relative impact of various growth and yield parameters on rice grain yield. The data revealed that, apart from 1000-grain weight, all other growth and yield parameters, such as plant height, tiller density, dry matter accumulation, leaf area index at 60 DAT, and number of filled spikelets per panicle, were significantly correlated

with rice grain yield. Therefore, it could be inferred from the given matrix that enhanced vegetative growth and a greater size of the sink have a marked influence on the grain yield of rice.

Grain yield and straw yield

The perusal of data in Table 4 indicated that the highest grain of rice was recorded by SI₉₀. The increased nitrogen application above the recommended dosage is likely attributed to achieving comparable grain yield CN₁₂₅, LCC₄, and NU₁₀₀ with SI₉₀ by expanding the sink capacity. The increased application of phosphorus and potassium beyond the recommended levels, as in the case of CN₁₂₅, could not have a marked impact on the grain yield of rice at the same nitrogen level (SI₉₀). Moreover, the SI₉₀ recorded a significant increase in grain yield by 17.06% compared to CN₁₀₀. Similar findings were observed by Sagar et al. (2024) and Zhang et al. (2024). Surprisingly, the highest straw yield of rice was recorded by CN₁₂₅. This might be attributed to enhanced straw rigidity and quality by the application of increased nitrogen, phosphorus and potassium levels. Moreover, the former treatment was on par with SI₉₀, LCC₄, NU₁₀₀, and CN₁₀₀, indicating that the enhancement in straw quality could be achieved by managing the optimal nitrogen quantity at the most sensitive stages of crop N demand. The lowest and significantly lower grain and straw yield compared to all the nutrient management treatments was noted by NM₀. These results corroborate the findings of Mir et al. (2025) and Pathak et al. (2025).

Table 4. Influence of different nutrient management strategies on grain and straw yield of rice.

Treatments	Grain yield (t ha ⁻¹)	Straw yield (t ha ⁻¹)
NM ₀	2.65±0.84 ^f	3.58±2.04 ^d
CN ₇₅	3.79±1.67 ^c	4.65±3.82 ^c
CN ₁₀₀	4.63±1.73 ^{bcd}	5.52±2.07 ^{abc}
CN ₁₂₅	5.34±3.02 ^{ab}	6.12±3.68 ^a
NU ₇₅	4.30±4.51 ^{de}	4.88±3.79 ^{bc}
NU ₁₀₀	4.95±1.95 ^{abcd}	5.70±1.36 ^{ab}
LCC ₃	4.41±1.40 ^{de}	4.98±5.01 ^{bc}
LCC ₄	5.20±1.03 ^{abc}	5.98±1.72 ^a
SI ₉₀	5.42±5.99 ^a	6.06±3.48 ^a
NE-R	4.20±2.36 ^{de}	5.31±4.11 ^{abc}
RCM-R	4.52±2.44 ^{cde}	5.54±1.95 ^{abc}
S.Em. (±)	0.26	0.32
CD (5%)	0.78	0.95

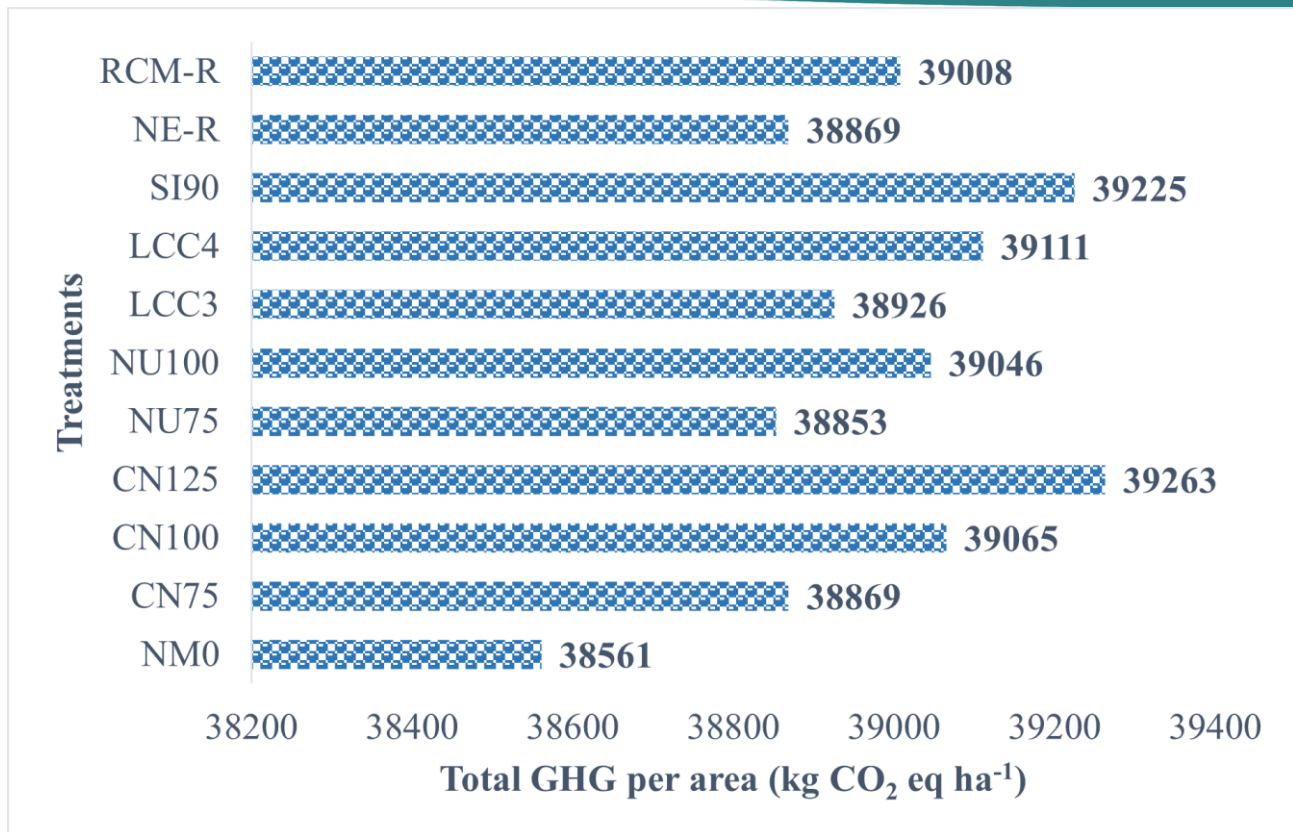


Figure 3. Influence of different nutrient management strategies on total GHG emission per area of rice.

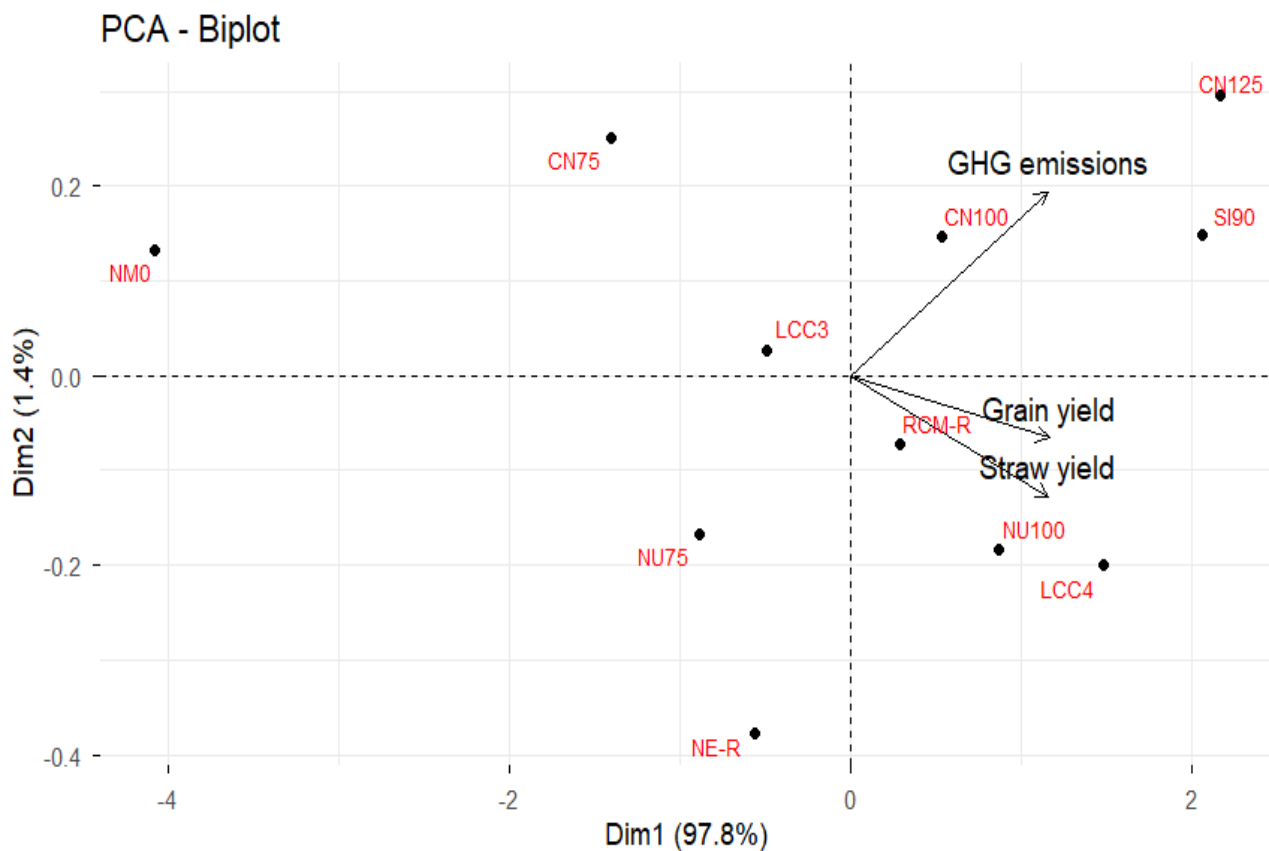


Figure 4. Principal component analysis biplot between nutrient management treatments, yield and GHG emissions.

Greenhouse gas emission

The total greenhouse gases (GHGs) estimated to be emitted by nutrient management treatments are presented in Figure 3. The results revealed that greenhouse gas emissions increased with the increase in nutrient application. The lowest emission was noted by NM₀ and CN₇₅, CN₁₀₀ and CN₁₂₅, respectively, and the progressively higher emission was noted. This might be due to increased nitrous oxide emissions. The NU₇₅ and NU₁₀₀ emitted comparatively lower GHGs than CN₇₅ and CN₁₀₀ due to their higher nutrient-use efficiency. Moreover, the site-specific nutrient management treatments registered moderately lower GHG emissions than the conventional practice due to lower nitrous oxide emissions. However, the change in methane emissions remains unaffected, as it is determined by soil organic carbon content under anaerobic conditions. These findings are consistent with those of Wang et al. (2024) and Sapkota et al. (2021).

Principal component analysis

The principal component analysis clearly classified the treatments based on their yield performance and greenhouse gas emissions (Figure 4). The first component accounted for 97.8% of % variation, while the second component accounted for only 1.4% of % variation. The treatments SI₉₀, CN₁₂₅, LCC₄, NU₁₀₀, and CN₁₀₀ were observed to show a positive association with grain and straw yield, indicating their role in enhancing crop productivity, while on the other hand, the treatments NE-R, NU₇₅, CN₇₅ and NM₀ were positioned on the negative side of the biplot, indicating relatively lower contribution to the yield. Interestingly, the greenhouse gas emission vector was positively associated with CN₁₂₅, CN₁₀₀ and SI₉₀. Among these treatments, SI₉₀ was relatively close to the yield vectors and far from the GHG emission vector, whereas CN₁₂₅ not only recorded higher grain and stover yields but also elevated GHG emissions, posing a serious threat to the environment.

Conclusion

In light of the above study, it can be concluded that SI₉₀ is a promising nutrient management strategy compared to conventional nutrient management because it ensures higher rice productivity with a moderate level of GHG emission. Therefore, it could be the most effective approach and future research on nutrient management should be focused on need-based nutrient application accompanied by crop intensification to provide adequate food to the growing population with a limited carbon footprint.

Conflict of interest

None

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How to cite this Article:

Lalichetti Sagar, Sagar Maitra, Sairam Masina and Sumit Ray (2025). Influence of Different Nutrient Management Strategies on Growth, Yield and Greenhouse Gas emissions of Irrigated Rice. *International Journal of Experimental Research and Review*, 49, 01-09.

DOI: <https://doi.org/10.52756/ijerr.2025.v49.001>



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